INTERMEDIATE-SCALE UNDERGROUND MAGAZINE

EXPLOSION TESTS

DECOUPLED GROUND MOTION EXPERIMENTS

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A series of decoupled detonations were conducted in a 1/3-scale underground magazine system. Chamber loading densities for these experiments were 1, 5, 15, and 42 kg/m^3. The Composition B explosive sources included cast cubes (20.3-cm), reclaimed flaked material and M-15 mines. Ground motion sensors were grouted into holes drilled into a side wall and the roof of the detonation chamber, and in the wall of the main drift out to the portal. In addition, seismic instrumentation was placed at selected sites up to 6 km from the center of the chamber. This paper presents an analyses of the measured data.

INTRODUCTION

The U.S. Army Engineer Waterways Experiment Station (WES) is currently conducting a research program in conjunction with the Republic of Korea to investigate new underground munitions storage concepts. The goal of this research is to develop magazine design features that will significantly mitigate the blast effects (primarily airblast and debris) that would escape out the entrance portal in the event of an accidental detonation of munitions stored in an underground magazine. A secondary concern is the effect on nearby structures of direct-induced ground motions generated by such an explosion. The conduct of large-scale tests in underground munitions storage chambers for this program provided a unique opportunity for the acquisition of ground motion data. The effect on nearby structures and adjacent storage magazines of direct-induced ground motions generated by such an explosion is an important factor in the siting and design of underground munition storage facilities. Ground shock is the controlling factor for determining the safe separation distance between adjacent storage chambers to prevent explosive communication or damage to stores, and for the design of shock mounts for auxiliary systems used in these facilities. The purpose of this paper is to review recently acquired, decoupled ground motion data and compare the results to the hazard criteria given in the current U.S. explosive safety standards (DOD 6055.9-STD, 1984).

The detonation of a store of munitions in an underground facility represents a complex explosion environment in which a number of parameters have a significant effect on the

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resulting ground motions. The dominant factor is the amount of explosive contained in a storage chamber of given volume, referred to as the loading density. Other factors include the type and distribution of explosives (e.g., distributed along the length of a long chamber, or concentrated), the amount of venting from the chamber into the tunnel system, and the properties of the rock surrounding the facility. The only factors which are accounted for in the current standards are the loading density and the properties of the surrounding rock, with the latter limited to material constants.

A ground motion hazard criterion is usually defined as a peak particle velocity at which a certain level of damage is expected. The current U.S. and NATO (NATO Document AC/258-D/258, 1991) standards quote 11.5 cm/sec and 23 cm/sec in soft and hard rock, respectively, as the acceptable levels for inhabited buildings. The distances to which these motion levels are expected to occur are defined as the Inhabited Building Distances (IBD) for ground motions. The maximum IBD (whether for ground motions, airblast, debris, etc.), in turn, are used to establish the safety hazard area around an explosive storage location.

This criterion is based upon predicting fully-coupled (i.e., when the explosive completely fills the volume of the chamber) peak particle velocity levels using empirical data, and applying a reduction or decoupling factor to account for the decoupled charge configuration (Odello, 1980). The decoupling factor is defined as the ratio of peak particle velocity at a given distance from a fully-coupled detonation to that from a decoupled detonation of the same charge weight. The velocity from a decoupled detonation is calculated from the equation:

$$V_d = D*V \qquad \textbf{(1)}$$

where V_d is the decoupled velocity, D is the decoupling factor, and V is the fully-coupled velocity.

This formula is used as the basis for calculating the IBD for explosions in rock chambers in both the U.S. and NATO standards. The benefit of this technique is that equations which predict fully-coupled motions can be used in conjunction with the decoupling factor to predict motions from decoupled charge configurations. The drawback is that little data exists to verify that the decoupling factor is accurate. The intermediate-scale explosion tests conducted in underground chambers for the U.S./Korea R&D Study provided an opportunity to acquire additional test data to evlauate the current formulas.

TEST DESCRIPTION

Phase I of the Intermediate-Scale Test Program was conducted in the Linchburg mine, near the town of Madalena, New Mexico. Figure 1 is a plan view of the mine. The existing mine drift was used as the access tunnel to two newly-constructed side drifts, where six simulated storage chambers. Each chamber represents a different chamber access configuration. The chambers and newly-constructed drifts were designed to be approximately 1/3-scale of an

actual underground magazine. The tests described in this paper were conducted in Chamber 4 in the left drift.

Figure 2 is a plan view of the left drift, showing the orientation of Chamber 4 with the left access drift. The dimensions of Chamber 4 were 4m wide by 8m lon~by 2m high, with a slightly arched cross-section, giving a total chamber volume of 71.5m^3.

This paper describes the ground motion data recorded on a series of four tests conducted in Chamber 4 (see Table 1). The tests ranged in charge weight from 71.5 kg to 2562.5 kg, which covers a range of loading densities from 1 to 42 kg/m^3. All tests used explosive charges constructed of cast Composition B cubes, each 203mm on a side, and weighing 14.3 kg.

Two arrays of accelerometers were placed in boreholes extending from Chamber 4, one vertical and one horizontal, with the gages oriented to measure radial acceleration. Each array contained four measurements at 4, 8, 16, and 32m from the center of the chamber (see Figure 2). In addition, acceleration measurements were made in the wall of the main mine tunnel at ranges of 77. 1 and 235.7 m from the center of Chamber 4.

RESULTS

Table 2 lists the peak motion data for each test and each measurement location. The acceleration-time waveforms were integrated to obtain velocity-time waveforms. Measured peak particle velocities versus scaled distance is plotted in Figures 3 and 4 for each of the tests, along with a first-order fit of the data. In each test, the peak velocities attenuate at about the same rate, as expected, and the amount of data scatter for each test is normal for measurements of this type.

Included in Figures 3 and 4 is the DDE5B hazard criterion for ground shock damage to inhabited buildings for sites located over hard rock, along with a comparison between the IBD calculated from the U.S. standards, and the distance at which the measured data indicate the hazard criterion was reached. Comparing the DDE5B-predicted range for each test with the measured range, we conclude that the DDE5B standards under-predict the ground shock IBD for the lower loading densities (Tests 2 and 3), and over-predict the IBD for the higher loading densities (Tests 5 and 6) of this test series.

The reason for the discrepancy between the predicted and measured IBD can be seen by comparing the motions expected from the tests using a fully-coupled orediction equation for peak particle velocities (McMahon, 1992), with the actual peak particle velocities measured. Figure 5a shows the fully-coupled predicted peak velocity, along with a prediction for each test that was derived by reducing the fully-coupled motions by the decoupling factor D, defined as:

$$\boldsymbol{D = 0.035 \left(\frac{W}{V}\right)^{1/2}} \qquad \textbf{(2)}$$

where W is the charge weight in kg and V is the chamber volume in cubic meters.

Figure 5a indicates that, if the model used in the standards is accurate, there should be significant variations in the motions measured at the same scaled distance for the loading densities used in this test area. Figure 5b, which is a plot of velocity versus scaled distance curve fits from each test, does not show this to be the case for this series of tests. With the exception of Test 2, Figure 5b shows that the motions at a given distance from the charge vary only with the net explosive weight, and not with the amount of decoupling (i.e., loading density), of the explosive mass in the storage chamber.

CONCLUSIONS

the ground motion measurements obtained during Phase 1 of the Intermediate-Scale Test Program provide an excellent set of decoupled ground motion data from large-scale explosion tests in underground chamber. Comparisons with the DDESB equation for ground shock IBD show a discrepancy between the measured and calculated distance to the IBD. This indicates that the current method for handling ground motions from decoupled detonations in rock may not be satisfactory, at least for the loading densities and chamber configurations tested.

Additional tests are planned at the Linchburg Mine test site that will provide further insights into the current discrepancy. These include a fully-coupled test, which will enable a more specific calculation of the actual decoupling factors for Tests 2, 3, 5, and 6, for a direct comparison with the decoupling equation.

ACKNOWLEDGEMENT

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TABLE 1. INTERMEDIATE SCALE UNDERGROUND MAGAZINE TESTS			
TEST NUMBER	CHARGE WEIGHT (kg)	CHARGE TYPE	LOADING DENSITY (kg/m^3)
2	71.5	CAST COMP B	1
3	343.0	CAST COMP B	5
5	943.2	CAST COMP B	15
6	2572.5	CAST COMP B	42

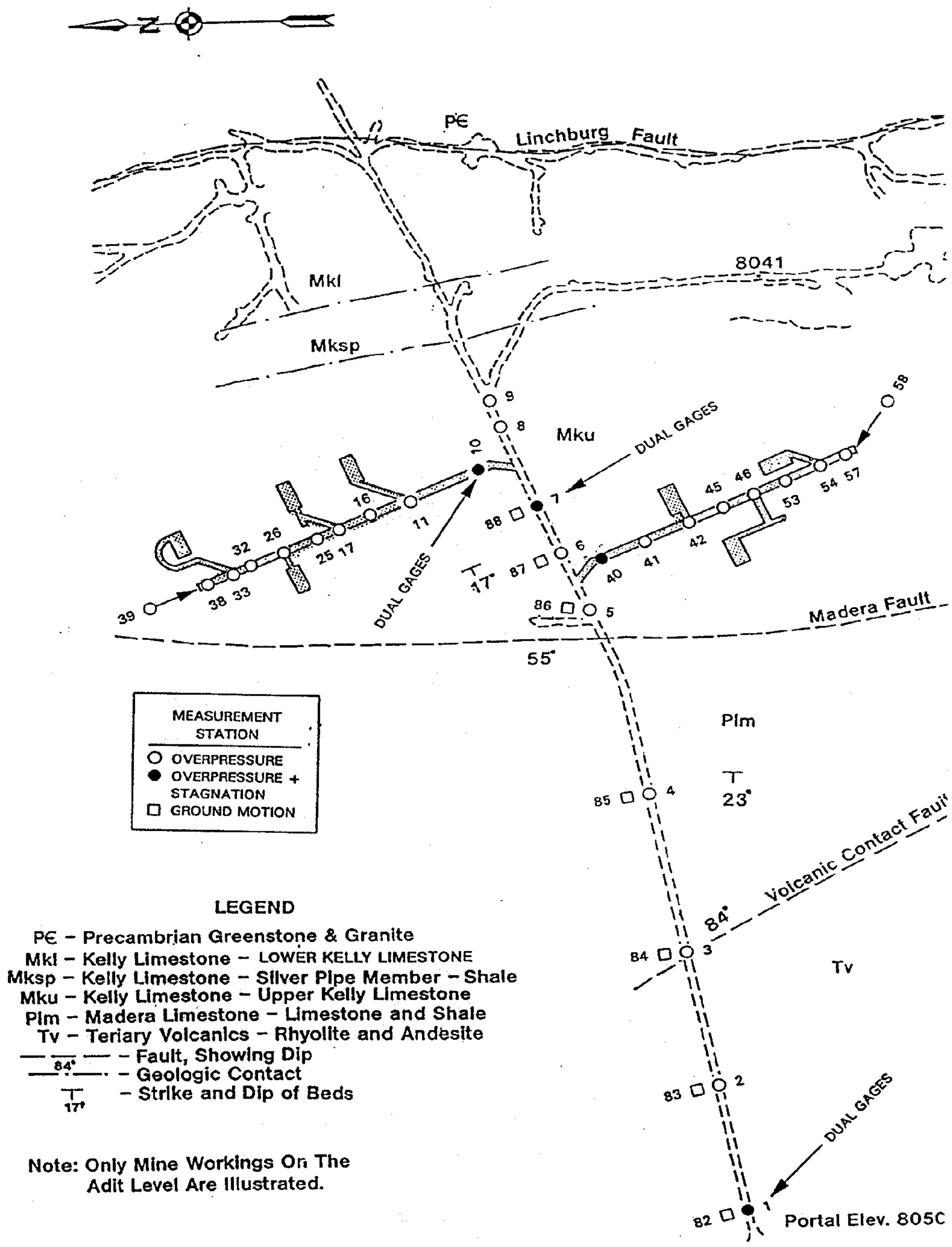
TABLE 1.
INTERMEDIATE SCALE UNDERGROUND MAGAZINE TESTS

TABLE 2. PEAK ACCELERATIONS AND VELOCITES

		TEST 2		TEST 3		TEST 5		TEST 6	
Measurement No.	Distance from Chamber Center, (m)	Peak Acceleration (G's)	Peak Velocities (m/sec)	Peak Acceleration (G's)	Peak Velocities (m/sec)	Peak Acceleration (G's)	Peak Velocities (m/sec)	Peak Acceleration (G's)	Peak Velocities (m/sec)
77A-AV-1	4.0	4000	3.72	12,800	13.4	Not Recorded		Not Recorded	
77A-AV-2	4.6	4200	3.69	b	b	a	a	Not Recorded	
77B-AV-1	8.0	276	0.34	1250	1.85	5000	5.9	8800	10.0
77B-AV-2	8.0	127	0.24	b	b	Not Recorded		b	b
77C-AV-1	16.0	20.2	0.068	84.4	0.33	258.3	0.86	376.0	1.36
77C-AV-2	16.0	18.1	0.066	b	b	238.8	0.85	Not Recorded	
77D-AV-1	32.0	Not Recorded		Not Recorded		8.29	0.096	16.1	0.19
77D-AV-2	32.0	0.91	0.0083	3.54	0.04	8.38	0.098	16.0	0.20
78-AR-1	4.0	Not Recorded		Not Recorded		6400	8.7	24,300	63.1
78-AR-2	4.0	4260	2.50	b	b	Not Recorded		19,200	63.6
79-AR-1	8.0	Not Recorded		Not Recorded		1442	2.4		
79-AR-2	8.0	71.3	0.16	440.	0.93	Not Recorded			
80-AR-1	16.0	Not Recorded		Not Recorded		Not Recorded			
80-AR-2	16.0	18.9	.056	b	b	377.0	1.0		
81-AR-1	32.0	Not Recorded		Not Recorded		22.5	0.14		
81-AR-2	32.0	0.70	.0071	b	b	20.5	0.13		
8-AR	77.1	0.25	.0027	1.38	0.014	5.44	.041		
7-AR	74.2	0.28	.0021	1.16	0.010	4.18	.030		
6-AR	75.9	0.12	.00089	0.66	0.0065	2.00	.022		
5-AR	84.4	0.14	.0011	0.84	0.0068	2.00	.022		
4-AR	119.8	0.025	.00036	0.15	0.0030	0.34	.0072		
3-AR	163.5	0.026	.00041	0.15	0.0026	0.27	.0054		

TABLE 2. PEAK ACCELERATIONS AND VELOCITES

Figure 1. Plan view of Linchburg Mine showing left and right



PLAN

Figure 1. Plan view of Linchburg Mine showing left and right drifts constructed for the Intermediate Scale Test Program.

Figure 2. Plan view of left access drift showing the orienfation of chamber 4, the horizontal bore holewith ground motion gage locations, and the location 01 the vertical borehole in chamber 4.

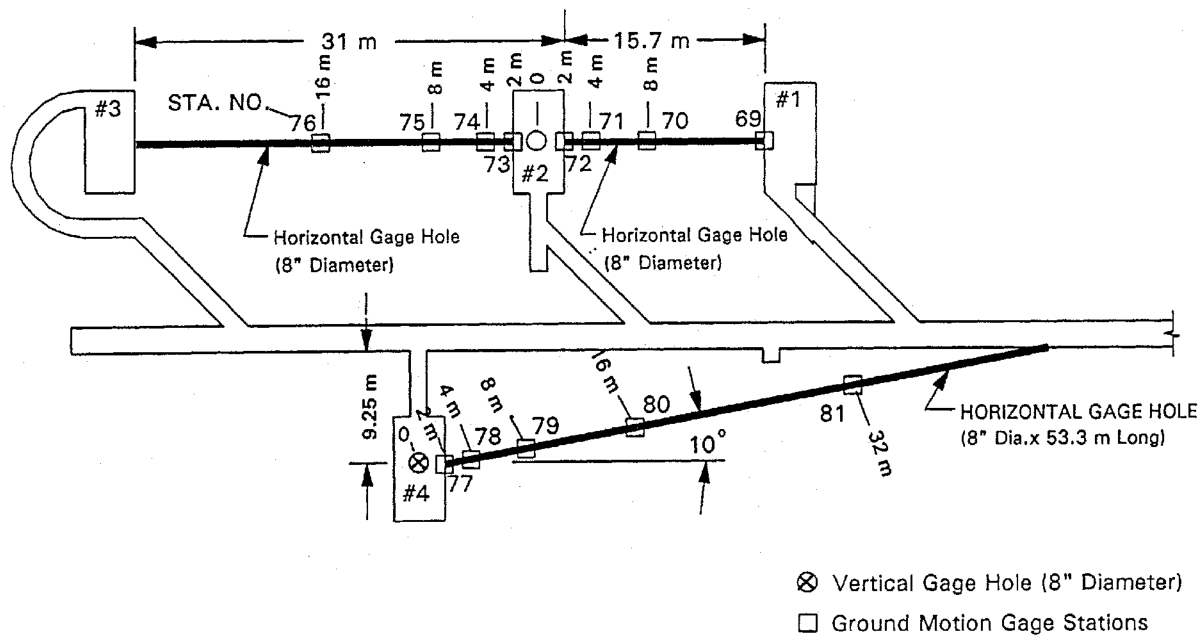


Figure 2. Plan view of left access drift showing the orientation of chamber 4, the horizontal borehole with ground motion gage locations, and the location of the vertical borehole in chamber 4.

Figure 3. Measured lLeak particle velocity versus scaled distance for tests 2 and 3. Also shown is the criterion for hard rock (.23 m/sec), the Inhabited Building Distance for each test (in terms 01 calculated from the U.S. standards, and the distance at which the measured data indicate the reached.

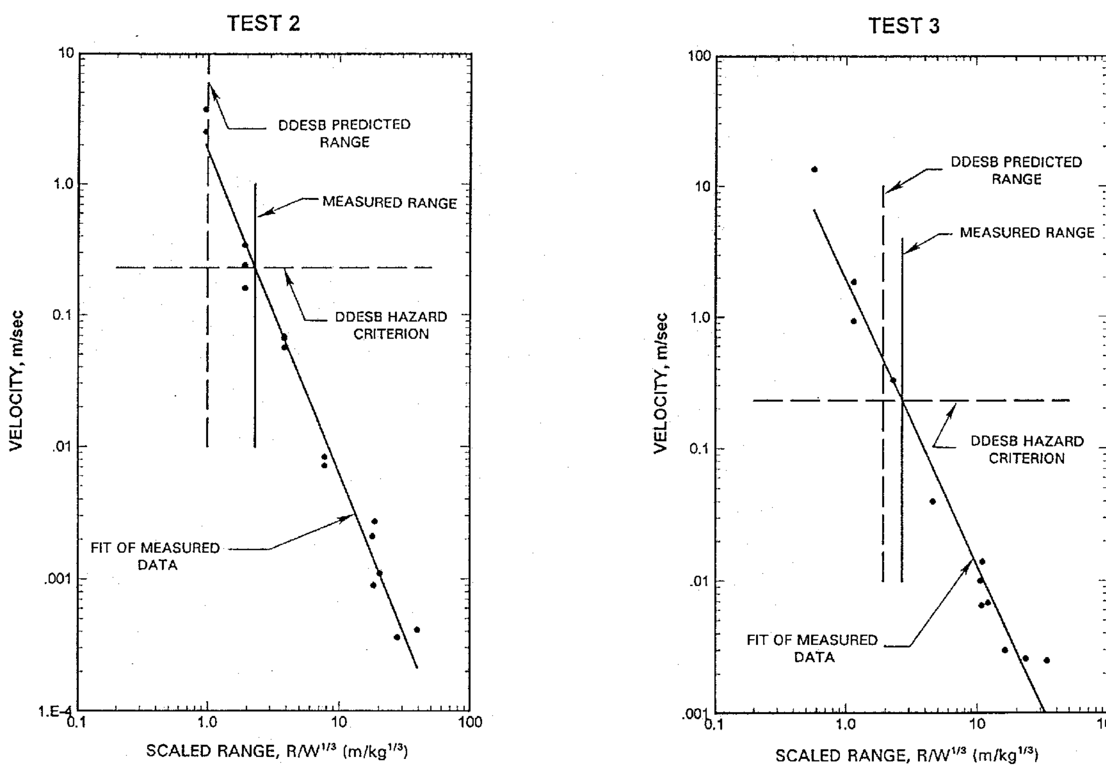


Figure 3. Measured peak particle velocity versus scaled distance for tests 2 and 3. Also shown is the DDESB hazard criterion for hard rock (.23 m/sec), the Inhabited Building Distance for each test (in terms of scaled range) calculated from the U.S. standards, and the distance at which the measured data indicate the hazard criterion was reached.

Figure 4. Measured peak particle velocity versus scaled distance for tests 5 and 6. Also shown is the criterion for hard rock (.23 m/sec), the Inhabited Building Distance for each test (in terms o calculated from the U.S. standards, and the distance at which the measured data indicate the reached.

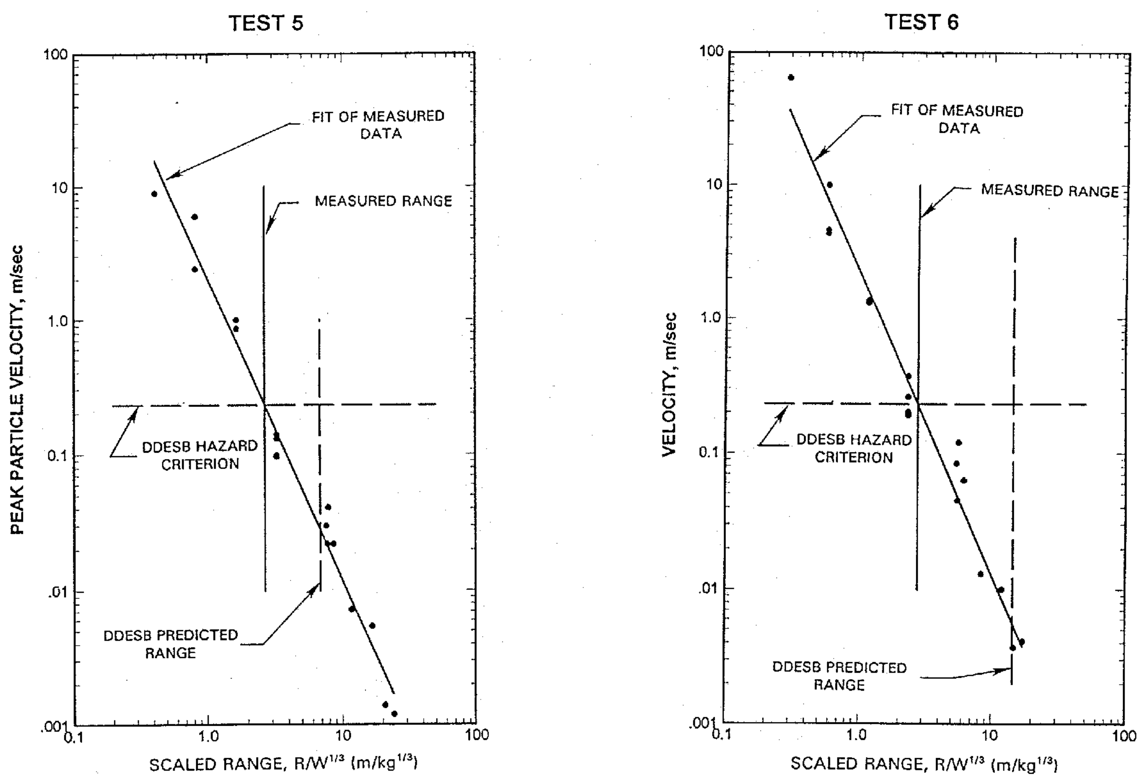


Figure 4. Measured peak particle velocity versus scaled distance for tests 5 and 6. Also shown is the DDESB hazard criterion for hard rock (.23 m/sec), the Inhabited Building Distance for each test (in terms of scaled range) calculated from the U.S. standards, and the distance at which the measured data indicate the hazard criterion was reached.

Figure 5. Comparison of peak particle velocities showing the expected reductions in motions based on factors calculated from equation 2 applied to the fully coupled case (a), and the measured m(to the measured data (b) The measured motions do not exhibit the expected reductions in ni scaled range.

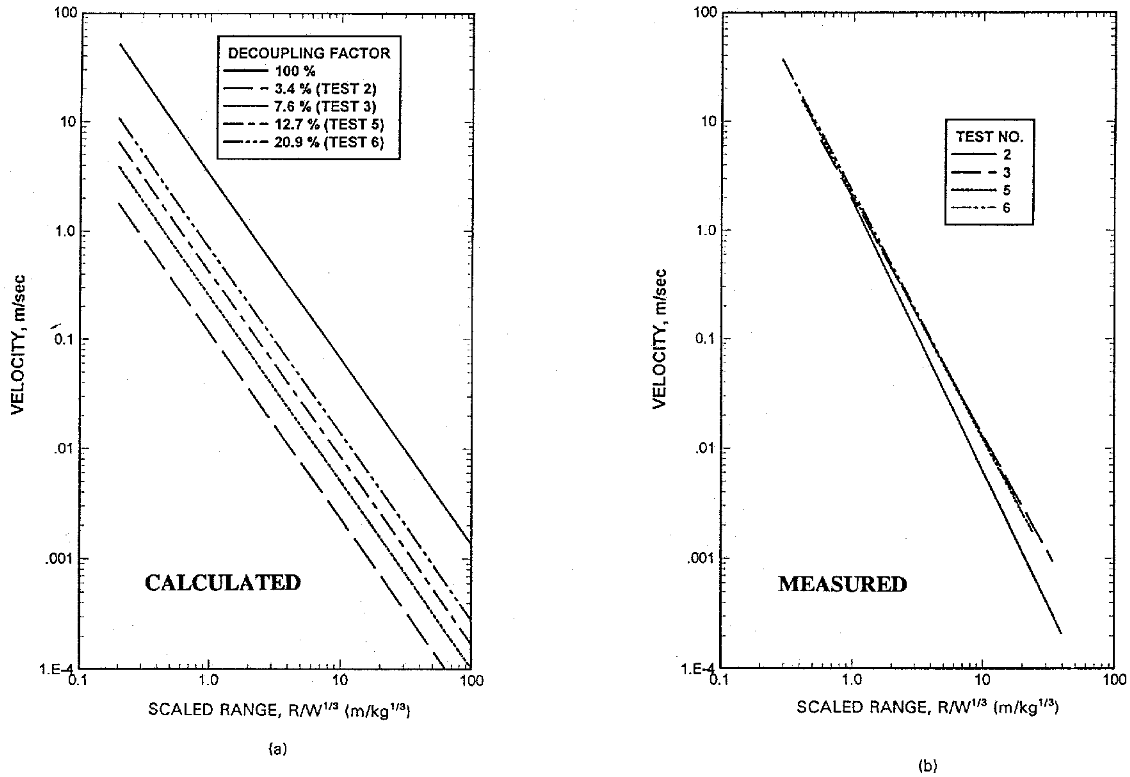


Figure 5. Comparison of peak particle velocities showing the expected reductions in motions based on the decoupling factors calculated from equation 2 applied to the fully coupled case (a), and the measured motions in terms of fits to the measured data (b). The measured motions do not exhibit the expected reductions in motions at the same scaled range.